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(54) Linear power control for ultrasonic probe with tuned reactance.

(57) There is disclosed herein a driver system for an ultrasonic probe for allowing a user to have proportional control of the power dissipated in the probe in accordance with the position of power dissipation controls operable by the user and for automatically tuning upon user request such that the driving frequency is equal to the mechanical resonant frequency of said probe and such that the reactive component of the load impedance represented by said probe is tuned out. The system uses a tunable inductor in series with the piezoelectric crystal excitation transducer in the probe which has a flux modulation coil. The bias current through this flux modulation coil is controlled by the system. It is controlled such that the inductance of the tunable inductor cancels out the capacitive reactance of the load impedance presented by the probe when the probe is being driven by a driving signal which matches the mechanical resonance frequency of the probe. The resulting overall load impedance is substantially purely resistive. The system measures the phase angle and monitors the load current. This information is used to determine the mechanical resonance frequency by sweeping through a band of driving frequencies and finding the peak load current where the slope of the load current versus frequency function is greater than a predetermined constant. After the automatic tuning to the resonant frequency, the system automatically adjusts the bias current flowing through the flux modulation coil to maintain the substantially purely resistive load impedance for changing power levels. There is also disclosed herein an analog circuit to measure the Phase angle for the load driving signal and to adjust the frequency of the driving signal for best performance. This system includes an integrator to eliminate the effect of offset errors caused by operational amplifiers.

LINEAR POWER CONTROL FOR ULTRASONIC PROBE WITH TUNED REACTANCE

Background of the Invention

The invention relates to the field of phacoemulsification probe driving apparatus, and, more particularly, to the field of tuned reactance process for phacoemulsification.

It has long been known that, in delivery of electric power to inductive loads or capacitive loads, maximum efficiency and maximum delivery of said power occurs when the phase angle between the voltage across the load and the current through the load is zero. The phase angle of a system is related to the power factor. Those skilled in the art appreciate that impedance of any network which includes inductive or capacitive elements in addition to resistive elements is the vector sum of the real component, i.e., the resistive elements, and the imaginary component caused by the presence of the inductive and capacitive elements. If the reactive component is zero, then the impedance of a system is purely resistive, and the resultant vector is coincident with the real axis. In such a circumstance, the phase angle is zero. Power factor is a measure of the relative magnitudes of the reactive and real components in a load impedance. It is related to the relative magnitude of these two vector components.

Power factor is also a measure of the efficiency, of a system in delivering power to a load. Since only resistive components can actually dissipate power, the presence of an inductive or capacitive reactance component in a load impedance will decrease the efficiency of power delivery of the system, since it causes increased power dissipation in the source resistance of the power supply. The reason for this is well understood by those skilled in the art and will not be detailed here. As a consequence of the foregoing reality, it has long been known by utility companies and other practitioners of the power delivery art that to maximize the efficiency of power delivery to a load, it is useful to tune out the reactive component of the load impedance by placing it in series or parallel with an equal and opposite sign reactive component in a tuning circuit so that the resultant load impedance is purely resistive. In such a circumstance the source impedance is said to be the matched conjugate of the load impedance, and the power delivered to the load is maximized.

Power delivered to a load is given by the following expression:

(1) Power = VI cos theta

where V is the voltage drop across the load impedance, and I is the series current flowing through the load impedance, and cos theta is the power factor of the circuit. The power factor is said to be "leading" if the current leads the voltage, and "lagging" if the current lags the voltage.

Ultrasonic probes have traditionally been used for phacoemulsification for rupturing of cataracts in the eye coupled with aspiration of the pieces of tissue disrupted by the probe. There have been developed two classes of probes, one of which is excited by piezoelectric crystals. Such piezoelectric probes traditionally have been rods of metal, such as titanium, having piezoelectric crystals affixed therein to act as excitation sources to cause the rods to vibrate. The piezoelectric crystals are driven with electrical alternating current driving signals having high frequencies, such as 40,000 Hz. The length of the probe is such that it is a multiple of one-half the wavelength of the driving signal. Vibration of the piezoelectric crystal under the influence of the driving signal causes the rod to vibrate at its mechanical resonant frequency.

The piezoelectric crystals which are used as excitation sources in such probes, when coupled with the mass of the probe rod, can be modeled as an equivalent electrical circuit having inductive, capacitive, and resistive components. There is a capacitive component representing the elasticity of the metal of the rod and inductive component representing the mass of the probe. There is also a resistive component representing resistance to motion of the tip of the rod as it hits loads such as tissue or fluids in the eye which tend to dampen the vibration of the tip of the probe. The piezoelectric crystal itself contributes a resistive component which is related to the amount of leakage of current between the terminals of the crystal. The crystal also has a capacitive component which represents the intrinsic electrical characteristics of piezoelectric crystals, i.e., the thickness and the dielectric constant and the area.

As the temperature changes, and as load on the probe changes, the various resistive and reactive components in the equivalent circuit of the probe change values. These changes in the component values change the mechanical resonant frequency of the probe. Unless the driving frequency is changed to correspond with the changed resonant frequencies, maximum power-transfer efficiency will not be achieved.

Further, those skilled in the art understand that maximum power transfer between a source and a load occurs when the impedances of the source and the load are matched so that the load appears to be purely resistive. Therefore, in the case of an ultrasonic probe if the probe load impedance at the resonance frequency has a capacitive reactive

to sense the power factor or phase angle between the phasor representing the current waveform for current flowing through the piezoelectric crystal load and the waveform representing the driving voltage across the piezoelectric crystal load. A phase detector is used for this purpose. It has one input which samples the voltage waveform for the driving voltage across the crystal and it has another input which samples the current waveform for the driving current through the crystal. This current waveform sampling is taken from a current sensor in series with the primary side of the voltage step-up transformer. The feedback voltage from this current sensor is proportional to and in phase with current flowing through the primary of the step up transformer. It is the phase angle between the current flowing in the primary and the voltage across the primary as indicated by a SYNC signal from the voltage-controlled oscillator which is in phase with the driving voltage which is tuned by the system to be zero or some other user defined acceptable phase angle so as to cancel the reactance component of the load. Any other means of sensing the phase of the load current will also suffice for purposes of practicing the invention.

The phase detector generates two pulse-width modulated digital signals which represent the magnitude of the phase and its sign. These pulse-width modulated signals are summed and integrated to generate an analog signal representing the magnitude of the phase angle error. This analog signal is converted by an A/D converter to a digital number representing the phase angle error. Any phase angle other than zero represents an out-of-tune condition where the reactance of the probe impedance is not canceled. When the phase angle is nonzero (or whatever acceptable phase angle the user sets in some embodiments), the microprocessor senses this fact and alters the DC current flowing through the magnetic flux modulating coil in the tuning inductor. This alters the amount of magnetic flux in the core passing through the AC driving coils of the tuning inductor, thereby altering the inductance thereof. This process is continued with small changes to the drive current of the D.C. coil until the reactive component of the probe impedance is canceled and the source drive impedance is a matched conjugate of the probe impedance.

In the preferred embodiment, a sweeper software routine sweeps the driving frequency through a range of frequencies known to include all possible mechanical resonant frequencies of commercially usable phacoemulsification probes. During this sweep, the probe drive current is monitored and compared to the highest probe driver current to that point in time. If the current frequency of the driving signal results in a probe drive current which is greater than the current highest probe driver current, the current probe driver current is replaced with the new highest probe driver current value. Slope calculations to determine the slope of the function of load current versus driving frequency are continuously performed. This process is continued until the entire range of frequencies has been surveyed. The frequency corresponding to the highest probe driver current having a slope which is greater than a predetermined constant is then set into the VCO by sending a signal to the frequency modulation input of the VCO causing it to generate a probe driving signal having the corresponding frequency. After the proper driving frequency is determined, a software routine to tune away the phase angle as much as possible is performed. This routine determines the phase angle difference between a constant reference phase angle representing the desired or unavoidable phase angle difference and the actual phase angle. The difference is then used to adjust the D.C. coil bias drive. This process of successive approximation is then continued until the phase angle difference falls within an acceptable range.

The methods of linear power control, impedance matching over wide ranges of conditions, and source frequency tuning to match the resonant frequency according to the teachings of the invention may be understood from the above description of the functions of the apparatus that implements these processes.

The teachings of the invention can be better understood by reference to the following drawings.

Brief Description of the Drawings

Figure 1 is a block diagram of the preferred embodiment of an apparatus according to the teachings of the invention.

Figure 2 is an equivalent circuit for the piezoelectric crystal and mechanical system of the probe.

Figures 3A and 3B are two expressions of the mathematical relationships needed to explain the functioning of the system.

Figure 4 is the simplified equivalent circuit of the probe at the mechanical resonant frequency.

Figure 5 is a symbolic diagram illustrating the interplay between the hardware and software elements of the system.

Figure 6 is a plot of a typical load current versus frequency function illustrating the precharge and postcharge regions symbolically.

Figure 7 is a flow chart of the "minimizer" routine to tune out the reactance component of the load impedance.

Figure 8 is a flow chart of the "def-phase" routine to set a default value for HENRY.

This compensation for the capacitive reactance of the probe load impedance is accomplished by use of a tuning inductor 36 having an inductance L_T. The tuning inductance consists of a ferromagnetic core having three legs labeled A, B, and C. Legs A and C have wound thereabout D.C. bias signal coils which are connected in series. The middle leg B has wrapped thereabout an A.C. driving signal coil. The purpose of this A.C. driving signal coil is to provide an inductance in series with the load impedance of the probe to help cancel the capacitive reactance of the load impedance at the mechanical resonant frequency. To that end, the A.C. driving signal coil establishes paths of magnetic flux which pass through the ferromagnetic material of legs A, B and C. When direct current is passed through the D.C. bias coils, the amount of magnetic flux in the ferromagnetic coil is altered. When the amount of flux in the core is altered, the inductance of the A.C. driving signal coil changes. Thus, by controlling the magnitude of current flowing through the D.C. bias coils 828 and 830 wrapped around legs A and C (hereafter sometimes referred to as the flux modulation coils) the inductance L_T of the tuning inductor, i.e., the A.C. driving signal coil 826, may be changed. The D.C. bias windings 828 and 830 must be such as to be able to alter the apparent inductance of the A.C. coil 612 between 0 and 30 millihenries.

The flux modulation coils 828 and 830 are coupled to the output of a voltage-to-current amplifier 38. This amplifier receives a voltage input signal from a D/A converter 40. The purpose of the voltage-to-current amplifier 38 is to convert the voltage on the line 42 from the output of the D/A converter to a corresponding magnitude of D.C. bias current flowing through the flux modulation coils 828 and 830.

The D/A converter 40 receives as its input a phase angle adjust digital word HENRY on the bus 46 from the microprocessor. This phase angle adjust word is generated by the microprocessor 808 in the process of running one of the programs described below.

HENRY is generated from certain items of data read by the microprocessor. One of these data items is the phase angle error word PHASE on a bus 818. This phase angle error data represents the phase angle between the phasor representing the driving voltage waveform applied across the crystal load and the phasor representing the current waveform for load current flowing through the crystal. This phase angle error information is developed in part by a phase detector 50. The output of the phase detector is coupled to a summer and integrator 52, which has its output 88 coupled to an A/D converter 54.

To understand how the phase angle error adjust signal is generated on bus 818, the rest of the driving circuitry will be explained as a preliminary matter. The function of the driving circuitry is to drive the crystals 28 and 30 with an A.C. driving waveform which causes the crystals to vibrate at the mechanical resonance frequency of the probe 24. Obviously, the first step in this process is to generate a driving signal having a frequency which is equal to the mechanical resonance frequency of the probe 24. This is done, in the preferred embodiment, by a voltage controlled oscillator 56. In the preferred embodiment, the voltage controlled oscillator includes a linear programmable amplifier.

The output signal of the voltage controlled oscillator on line 72 in Figure 1 is applied to the input of a linear driver amplifier 74. The purpose of this amplifier is to amplify the signal on the bus 72, and apply it to the primary winding of a voltage step-up transformer.

The driving signal on line 72 is generally a sinusoid having an RMS voltage level related to the desired power dissipation. This signal is amplified in a class AB mode by the driver amplifier 74.

The output of the amplifier 74 is applied to the primary of a voltage step-up transformer 76. A current sensing transformer 550 is coupled in series with the return line from the primary of the transformer to the operational amplifier 74. The secondary of the transformer 76 is coupled to the lines 836 and 838. The line 838 is coupled to one end of the A.C. driving signal coil 826 on the tuning inductor. The other terminal of coil 826 is coupled via a line 32 to one terminal of the crystals 28 and 30 (which are coupled in series). The line 836 is coupled to the return side of the piezoelectric crystals 30 and 28. Thus the current flowing in the secondary of the step-up transformer 76 is the series current flowing through the crystals 28 and 30 of the probe 24 and the A.C. signal driving coil 826.

The CPU 808 needs feedback signals regarding two things to do its tuning functions. First, the CPU 808 must know the phase angle difference between the driving signal voltage and the resulting load current. Also, the CPU must know the amplitude of the current flowing in the load. To determine the phase angle difference, the phase detector 50 and a current sensor transformer 550 are used. The phase detector has one phase input coupled by line 817 to the secondary winding of the current sensor 550 and has another phase input coupled to a signal SYNC on line 816 from the voltage control oscillator. As in the other embodiments described herein, when there is no phase difference, no pulses appear on either of the output lines 84 or 86. However, when positive phase difference exists, a train of pulse width modulated pulses appear on line 86 with the width of

power control, impedance-matching, and frequency-tuning functions of the invention by running a program stored in local RAM 90. This memory also includes ROM for storage of lookup tables and other information which does not change over the life of the system.

Referring to Figure 3, equation (A), there is shown the expression which defines the relationships which exist when the piezoelectric crystals are being driven at the resonant frequency of the mechanical system. Equation B in Figure 3 defines the value of the tuning inductance when it is in the tuned condition when the crystals are being driven at the resonant frequency of the mechanical system. Equation A represents the expression for the resonant frequency of the mechanical probe system for any particular temperature.

In Figure 2, the mechanical system is represented by the components in the equivalent circuit, labeled R_S, C_S, and L_S. The value of the component R_S represents the mechanical load engaged by the tip of the probe. The component C_S represents the elasticity of the metal in the probe. The component L_S represents the mass of the probe. The value of the components C_S change with changing temperature. The temperature may change either because the ambient temperature changes or because of power dissipated in the probe through excitation of the crystals. The value of the component R_S changes greatly with the loading of the probe.

The other components of the crystal/probe system equivalent circuit are C_P and R_P. The component C_P represents the parallel electrical capacitance of the crystals 28 and 30 in Figure 1. The component R_P represents the leakage of electrical current between the terminals of the crystals.

At the mechanical resonance frequency, the reactive component represented by C_S (jw C_S) is exactly equal to and opposite in sign to the reactive component L_S (1/jw L_S). Since these two reactive components cancel each other out, the equivalent circuit for the crystal/probe system is as shown in Figure 4. As can be seen from Figure 4, the equivalent circuit has a substantial capacitive reactance of the crystals 28 and 30. Thus the load impedance has a real component represented by the value of the resistors R_S and R_P in parallel, and a re active component of a capacitive nature represented by the capacitance C_P. According to the teachings of the invention, maximum power efficiency will be achieved by tuning the tuning inductor L_T so as to cancel out the reactive component and the load impedance represented by C_P. When the crystals 28 and 30 are driven at the resonant frequency of the mechanical system for any particular temperature, the necessary value for the tuning inductance is given by equation B in Figure 3.

As can be seen from equation B, the value for the tuning inductance is highly dependent on the value for the resistive components R_S and R_P and upon the value of the parallel electrical capacitance of the crystals 28 and 30. This means that the necessary value for the tuning inductance to keep the probe system in proper tune will change with changing temperature, changing loading conditions, and changes in the level of power dissipated in the probe by the driving system. The reason for this is that either changes in ambient temperature or power dissipation in the probe raises the temperature of the probe and therefore affects the elasticity of the material. This changes the value of the component C_S in the equivalent circuit of Figure 2 and therefore changes the mechanical resonant frequency as defined by equation A of Figure 3. Changing loading conditions also change the mechanical resonant frequency because, in addition to changing the value of R_S in Figure 2, changing load also affects the value of L_S because the load becomes an effective part of the mass of the system. This also changes the value of the mechanical resonant frequency defined by equation A by Figure 3.

There is also provided a watchdog timer circuit 602 which serves as a safeguard against software or computer failure. The watchdog timer is constantly counting up toward a timeout number and will be continually reset by the CPU 808 by a signal on the line 606 before the timeout number is reached as long as the CPU 808 is functioning properly. If the CPU gets trapped in an endless loop or somehow fails to reset the watchdog timer 602, the timer will time out and assert a nonmaskable interrupt on line 604. The CPU 808 is slaved to the nonmaskable interrupt and will always be vectored to the service routine which serves the nonmaskable interrupt regardless of whether the CPU is in an endless loop or not. This service routine shuts down the system as a safety precaution.

The voltage-controlled oscillator/programmable gain amplifier 56 has two frequency control inputs: a coarse input 800 and a fine input 802. These two inputs receive the signals COARSE and HERTZ, respectively, from digital-to-analog converters 804 and 806, respectively. These digital-to-analog converters receive digital signals from the CPU 808 on lines 810 and 812, respectively. These digital signals define the analog levels for the signals on lines 800 and 802 and thereby control the frequency of the output drive signal DRIVE FREQUENCY from the voltage-controlled oscillator on line 72.

Each of the digital-to-analog converters 804 and 806 receives a reference voltage from a preci-

some embodiments, the "sweeper" routine is performed periodically and in some embodiments, the "sweeper" routine is performed only when called by the main loop under conditions such as power being first applied to the handpiece, a new handpiece is attached etc. Thus, as conditions such as probe temperature and load change so as to alter the resonance frequency of the probe, the new resonance frequency is found in some embodiments, and the voltage-controlled oscillator is commanded through the digital signals on line 810 and 812 to deliver the drive signal on line 72 at the new resonance frequency.

The CPU 808 from time to time also checks the phase angle difference between the drive signal voltage and the load current through monitoring of the signal PHASE on line 818. In the preferred embodiment, this process is stopped and the tuning inductor is tuned to minimum inductance during a resonance tuning interval when the "sweeper" routine is active in tuning the voltage-controlled-oscillator. A "minimizer" software routine performs the phase angle tuning after the "sweeper" routine finishes its process of locating the mechanical resonance frequency and tuning the VCO to output a drive signal at this frequency. When the "minimizer" routine is active, and the phase angle difference becomes larger than a desired value, the CPU 808 acts through a digital-to-analog converter 40 and an amplifier 38 to alter the inductance of a tunable inductor 36 so as to cancel the capacitive reactance of the load. This minimizes the phase angle difference between the driving signal voltage and the load current. The inductance of the tuning inductor is altered by changing the flux in the tuning inductor core through use of D.C. bias coils 828 and 830. These bias coils are connected in series and are driven by the signals FLUX COIL BIAS 1 and FLUX COIL BIAS 2 on the lines 832 and 834. The D.C. bias existing between the lines 832 and 834 is controlled by a digital signal HENRY on line 46 from the CPU 808. This digital signal is input through the digital-to-analog converter 40, which also receives a D.C. voltage reference level signal REF 4. The digital-to-analog converter converts the digital level represented by the signal HENRY to an analog signal on line 42 which controls the output of an amplifier 38 so as to drive the signal lines 832 and 834 with the appropriate D.C. bias level.

Finally, note that the drive signal to the probe handpiece on lines 836 and 838, i.e., the signals DRIVE 1 and DRIVE 2, respectively, are coupled through the tunable inductance coil 826 such that the DRIVE 2 signal is coupled to the common node between the crystals 28 and 30 while the DRIVE 1 signal is coupled collectively to the outer nodes of the crystals 28 and 30. In other words, center drive between the two crystals 28 and 30 is used.

Referring to Figure 5, there is shown another representation of the combination of hardware and software which cooperates to implement the teachings of the invention. Again, like numbers between Figures 5 and 1 indicate that the circuitry is similar and performs a similar function. The handpiece is represented by the load 24. The variable frequency variable amplitude driving signal for the load appears on the line 836/838 and is generated by the driver 74/76. The circuitry inside the dashed line 56 represents the voltage-controlled oscillator 842 and the linear programmable amplifier 840. The gain control signal to the linear programmable amplifier 840 is the PWR LEVEL signal on line 814. The voltage-controlled oscillator 842 has a fine frequency control signal HERTZ on line 802 and a coarse frequency control signal COARSE on line 800. Power dissipation is controlled by a linear power delivery software routine 844 combined with the CPU 808 an a foot-operated control 68. This power delivery routine 844 generates the signal PWR LEVEL on line 814. The power delivery routine 844 has two interlocks represented by the TUNE flag represented by line 846 and the STOP POWER flag represented by the line 848. The TUNE flag will be set when a tuning routine called "sweeper", represented by box 850, indicates that the load 24 has not been properly tuned and that power should not be applied. The STOP POWER flag represented by line 848 will be set when a ground fault detect routine represented by box 852 indicates that a ground fault has been detected. A ground fault occurs any time certain conditions of three bits stored in a latch 823 occur. These three bits are set, respectively, by the presence of the SYNC output signal on line 816, presence of an output on line 824 from the current sensor and the presence of a connected handpiece as indicated by a signal HANDPIECE CONNECTED on line 825. A typical ground fault condition would be that no handpiece is connected. Another would be that there is a SYNC output signal but there is no output signal on line 824 indicating that no load current is flowing.

The current through the load 24 is sensed by the current sensor 550. The current sensor is coupled to a shaper circuit 854 to condition the signal on line 824 for use by the phase detector 50. The phase detector also receives the SYNC signal on line 816 through a shaper 856 which serves to condition the SYNC signal for use by the phase detector 50. The phase detector is a Motorola MC4044 integrated circuit in the preferred embodiment.

The phase detector output is coupled by a compensation network 52/54 to the CPU (not separately shown). The output of the compensation network is the signal PHASE on line 818.

frequency. The software of the "sweeper" routine also performs specific operations during a "precharge" interval to improve performance of the servo loop for tuning the tunable inductor. During the "precharge" interval, the software of the "sweeper" routine causes the CPU to output a predetermined value for the control signal HENRY. After this predetermined level is established, a delay is imposed to allow the inductance of the tuning inductor to change to the new value established by the value of the control signal HENRY. No changes in the drive frequency to the probe are allowed during this delay of the "precharge" interval. During the "precharge" interval, the value of the control signal HENRY is changed to a very large voltage so as to cause the D.C. bias coils 828 and 830 in Figure 1 to saturate the core of the transformer 36 with magnetic flux. This minimizes or eliminates any inductive characteristic of the tuning coil 826. This is desirable so that the inductance of the tuning inductor does not play a role in establishing the resonant frequency found by the "sweeper" routine. Since the reactance of an inductor changes with changing frequency, having the tuning inductor in the circuit during a sweep could lead to a false resonance. The "precharge" routine eliminates the possibility.

Referring to Figure 7, there is shown a flow chart for the "minimizer" routine 866 in Figure 5. This routine starts at step 880 with a test to determine whether the foot switch is down, indicating that the surgeon desires to apply power to the probe and that the LOOP flag is in a state indicating that the "sweeper" routine has tuned the system such that the voltage-controlled oscillator is now operating at the resonance frequency of the probe. The purpose for step 880 is to not allow the "minimizer" routine to minimize the phase angle error unless power is being applied to the probe and the system has been tuned to the mechanical resonance frequency of the probe. The "minimizer" routine is called 30 times per second by a timed interrupt. Thus the PHASE minimization function of the "minimizer" routine is performed in background to the operations in the main loop.

If both the foot switch is down and the LOOP flag indicates that tuning of the tuning conductor is permissible, processing advances to step 882. In this step, a variable SUPPRESS is tested to determine if its value is greater than 30. The SUPPRESS variable is a variable which is used to cause a delay of one second from foot pedal depression before any further corrections of the control signal HENRY are allowed. Since the "minimizer" routine is called 30 times per second, and the SUPPRESS variable is incremented by 1 by step 884 upon each call until the SUPPRESS variable has a value greater than 30, a one second delay is thereby implemented. The purpose for this delay is to improve the response of the system when the foot switch is first pressed by the surgeon. Because of the characteristics of the servo loop, when a servo correction is made, power dies momentarily while the servo loop stabilizes at its new operating point. This is because of the characteristics of the tuning inductor and the inability to change current flowing through an inductor instantaneously. Since the surgeon expects immediate response when the foot switch is pressed, the delay is used to not allow any corrections within the first second after depression of the foot switch so that power response appears to be instantaneous.

Returning to step 880, if the result of this test is false, meaning either that the foot switch is not depressed or that the LOOP flag indicates that the "sweeper" routine is still tuning, processing branches to step 886, where the SUPPRESS variable is set to zero. Thereafter, processing flows to step 888, where the value of the PHASE variable is arbitrarily set to the constant 2047. Normally the PHASE variable is set by the value of the PHASE control signal on line 818 received from the compensation network 5254 in Figure 5. However, the PHASE variable can be set at a constant, if desired. The value of the PHASE variable can vary from zero to 4095. The midpoint of this range is 2047 and corresponds to a zero-degree phase angle error. The phase angle range of 2047 ± 2047 corresponds to a phase angle error of plus or minus 180 degrees. Thus, step 888 is equivalent to arbitrarily setting the phase angle error at zero. Thereafter, processing flows to step 890 to exit the "minimizer" routine and return to the calling process.

Returning to step 882, if the value of the SUPPRESS variable is less than 30, the step 884 increments the variable by 1, and processing flows to steps 888 and 890. If however the value of the SUPPRESS variable is found to be greater than 30, the one-second delay implemented thereby has elapsed, and a correction of the phase angle error can begin. The first step in this process is symbolized by block 892 which calls the "default phase" subroutine.

Referring to Figure 8, there is shown a flow chart of the "default phase" subroutine called by the "minimizer" routine of Figure 7. The first step in the default phase routine is step 896, where the value of the PHASE variable is tested to determine if it is greater than the constant 2047. The PHASE variable will have been set by the value of the input signal PHASE on line 818 in Figur 5. Since the value 2047 for the PHASE variable indicates a zero degree phase angle, step 896 is a test for the existence of a positive phase angle. If the phase

age an "analysis" subroutine to be described further below. If for any reason the handpiece must be retuned, the second least significant bit of the MISTUNE variable will be set to a logic 1. This can occur when a new handpiece has been connected, or for other reasons such as a user request in some embodiments. For present purposes, the "analysis" subroutine should be understood as the software which causes the microprocessor to alter the frequency of the voltage-controlled oscillator until the mechanical resonance frequency of the handpiece is found or, for some reason, the resonance is not found and a FAILURE flag is set.

If the second least significant bit of the MISTUNE variable is found to be a logic 1, processing flows to step 936, which represents a call to the "cold-sweep" subroutine. The "cold-sweep" subroutine calls the "analysis" subroutine after setting up appropriate input conditions so as to tune the voltage-controlled oscillator. Upon return from the "cold-sweep" subroutine, the return step 938 in the "sweeper" routine is performed to return control to the calling process in the main loop (not shown).

If the second least significant bit of the MISTUNE variable is a logic 0, then processing flows to step 938, which represents a return to the calling process in the main loop. The details of the main loop of the program, including the calling process, are not critical to understanding the invention, and are not described further herein.

Referring to Figure 12A, there is shown a flow chart of the "cold-sweep" subroutine. The purpose of the "cold-sweep" subroutine is to tune the handpiece by invoking the "analysis" subroutine and to handle user interface functions in the form of audible feedback and a light-emitting diode on the front console to give the status of the tuning process. The "cold-sweep" subroutine also invokes the "postcharge" subroutine previously described. As earlier noted, the "sweeper" routine disables the PHASE "minimizer" routine 866 in Figure 5 through use of the LOOP flag 864 in Figure 5 during the tuning process.

To implement the function of visual feedback to the user, step 940 disables a light-emitting diode on the front panel near the connector where the handpiece is attached to the system. The next step, symbolized by block 942, is to cause this light emitting diode to blink. Thus, the user knows that a tuning process is underway when the light emitting diode is blinking.

It is important that only compatible phacoemulsification handpieces be connected to the system. To this end, a step 944 is performed to test the connected handpiece to determine if it is compatible. Any sensing scheme to determine the compatibility of the handpiece will suffice for purposes of practicing the invention, and the details of this sensing are not critical to understanding of the invention. If the test of block 944 determines that an incompatible handpiece has been connected to the system, then step 946 is performed to return processing to the calling routine, i.e., "sweeper", at step 938. Return step 938 then returns processing to the calling process in the main loop. Thus, when an incompatible handpiece is connected to the system, "cold-sweep" does not invoke the "analysis" subroutine, and no tuning can occur.

If test 944 determines that a compatible handpiece is connected, a step 948 is performed wherein a RANGE variable is set to a constant FULL. The RANGE variable is a control variable used to enable or disable performance of the "analysis" subroutine. If RANGE is set to full, the "analysis" subroutine will perform its tuning function. If, on the other hand, the RANGE variable is set to the value of a variable called MINIMUM, then the "analysis" routine will simply return immediately upon being called without having performed any tuning activity.

The next step in the "cold-sweep" routine is symbolized by block 950 on Figure 12B. This step sets the value of a variable called FAULT-CNTR equal to a constant called TRIES. This establishes the number of tuning attempts which will be made before a FAILURE flag is set indicating no successful tuning of the handpiece has been accomplished.

Next, the "cold-sweep" routine calls the "analysis" subroutine, as symbolized by block 952. The details of the "analysis" subroutine will now be described.

Referring to Figure 13, there is shown a fl w chart of the "analysis" subroutine. The first step in the "analysis" subroutine is a test to determine the value of the RANGE variable as symbolized by block 956. If the RANGE variable is equal to a constant called MINIMUM, then processing flows immediately to step 958, which returns processing to step 960 in the "cold-sweep" routine shown in Figure 12B. Processing by steps 960 and following of the "cold-sweep" routine will be described in more detail below. If the value of the RANGE variable is found to be not equal to the constant MINIMUM, then a step 962 is performed wherein the LOOP flag is set to a false condition. This disables the operation of the phase "minimizer" routine previously described.

Next, a step 964 is performed to call a WINDOW subroutine. This routine calculates the minimum frequency and maximum frequency between which the voltage-controlled oscillator will be tuned during the tuning process. Basically the window subroutine calculates a variable called MINIMUM which sets the lower boundary of the tuning window. In the preferred embodiment, the variable MINIMUM is set at zero. The "window" subroutine"

corded to date.

Step 983 sets the value of a variable RESONANCE equal to the value of the variable MINIMUM. The RESONANCE variable is used to record the value of the variable SWEEP-FREQ at the point where the mechanical resonance frequency of the handpiece has been found.

The step 984 sets the value of a variable SLOPE equal to the value of the variable MINIMUM. The SLOPE variable is used to record the result of the slope calculation performed in the "peak" subroutine shown in Figure 17A. Thus, steps 978 through 984 simply initialize the value of the various variables such that they are in a known state prior to calling the subroutine "peak".

Step 986 represents the call to the subroutine "peak". The details of the "peak" subroutine and the subroutines called by this subroutine will be discussed below. Upon return from the "peak" subroutine, the step 994 is performed. This step decrements a variable FAULT-CNTR and is performed upon each return from the "peak" subroutine indicating that a another try to find the resonance frequency has been performed. Once the "peak" subroutine is called, the variable SWEEP-FREQ is continuously incremented and load current tests and slope calculations are performed at the various operating frequencies until the upper frequency in the tuning window has been reached. At that time, peak returns to step 994 of the "analysis" subroutine indicating that a complete sweep through the current tuning window has been performed.

Next, a step 997 is performed wherein the value of the variable FAULT-CNTR is compared to zero to determine is the allotted number of tries or sweeps has been performed. If the allotted number of tries has been performed and no resonance frequency has been found, step 997 will find FAULT-CNTR equal to zero, and will branch to step 999 where an error message will be sent to the console. Thereafter, in step 1001, a FAILURE flag will be set indicating that no resonance frequency has been found in the allotted number of tries. Then, return step 958 is performed to return to step 960 of the "cold-sweep" subroutine.

Returning to consideration of the "cold-sweep" subroutine, step 960 tests the condition of the FAILURE flag. If it is set, step 1003 is performed to disable a blink routine to stop blinking of the light-emitting diode (LED) on the front panel of the system. Next, a step 1005 is performed to disable to LED thereby keeping the LED dark and indicating to the user that the tuning has not been successful for some reason. The user can then investigate the problem.

If the test of step 960 determined that the FAILURE flag is not set, then a successful tuning phase has been performed and the VCO is now tuned to operate at the mechanical resonance frequency of the probe. In this event, a call to the "postcharge" subroutine is performed as symbolized by step 1009. The flow chart for this subroutine is given in 15.

Referring to 15, the first step in the "postcharge" subroutine is to set the TUNED flag to enable the power delivery routine in the main loop to deliver power on demand to the handpiece. Next, a step 1013 is performed to set a LOOP flag to enable operation by the "minimizer" routine to tune away any phase angle.

A step 1015 sets a flag FS-DOWN to artificially simulate a request for power. This is done because part of the function of the "postcharge" routine is to apply power for 3 seconds to allow the handpiece and tuning inductor to settle at an operating point which will be somewhat close to the actual operating point which be set following the "postcharge" routine. To apply power, the flag FS-DOWN must be set.

Next, a step 1017 is performed to set the variable HENRY and control signal HENRY to the value of a variable PREDICTED. This variable is a statistically empirically determined value which approximates the normal operating point for the tuning inductor when coupled to most probes.

Step 1019 raises the BOUNDARY variable to send full power to the handpiece. This is followed by a three second delay/settling time symbolized by step 1021.

Finally, in steps 1023 and 1025, respectively, the old boundary value is set to restore power to its original level and the old FS-DOWN flag status is restored. Processing then flows via step 1027 to step 1033 in the "cold-sweep" routine to enable the LED thereby indicating to the user that a successful tuning phase has been completed. Next, a step 1007 is performed to set a RELAPSE flag. This causes an elapsed timer to be reset to zero time. The elapsed timer is used to control a display on the front panel used by the user to keep track of how much energy has been dissipated inside the eye.

Returning to consideration of "cold-sweep", an optional step 1029 is performed to sound a tone or play a tune to indicate that the machine is done with the tuning phase and reminding the user to check the LED for status.

Step 1031 resets the bit of the MISTUNE variable that controls access to the ANALYSIS routine thereby disabling the analysis routine until the next call thereto.

Finally, a step 1033 is performed to turn off the VCO thereby preventing amplification of noise, and processing returns to step 938 of "sweeper" and thence to the calling process in the main loop.

performed to call the "recorder" subroutine. No new I-PEAK is recorded. If CURRENT is greater than I-PEAK, then a test 1068 is performed to determine if SWEEP-FREQ is within the lower reject range which is defined as the lower 25% of frequencies in the current tuning window. If this condition is true, a jump to again along line 1064 occurs and "recorder" is called and no new I-PEAK is recorded. If SWEEP-FREQ is not within the lower reject range, the test of step 1070 is performed to determine if SWEEP-FREQ is within an upper reject range. This range is defined as the upper 25% of frequencies in the current tuning window. If this condition is false, step 1072 is performed to record CURRENT as the new I-PEAK. If SWEEP-FREQ is within the upper reject range, a jump to again along line 1064 is performed.

After step 1072 is performed, a call to the "detector" subroutine is performed where the slope of the load current versus frequency function is compared to a constant. The slope is calculated by the "recorder" subroutine, so examination of that routine is now in order.

Referring to Figures 18A and 18B there is shown a flow chart of the "recorder" routine. The first step is to set a variable COUNTER to COUNTER + 2 as symbolized by step 1076. COUNTER is a pointer in a circular buffer used to store load current samples or points on the load current versus frequency curve. Each load current sample is two bytes in length, so incrementing the COUNTER is done by adding 2 to point to the next pair of addresses. This incrementation is symbolized by step 1076. Next, COUNTER is tested against zero in step 1078. If COUNTER has reached zero, the buffer has been filled (it is filled from the highest pair of addresses to the lowest pair of addresses), and COUNTER is reset to the top of the buffer by setting it equal to a constant BUFF-SIZE in step 1080. BUFF-SIZE is equal to the size of the buffer. If test 1078 determines that COUNTER is not zero, a step 1082 is performed to set an address pointer POINTER equal to BUFFER + COUNTER. BUFFER is the lowest address in the circular buffer, so step 1082 sets POINTER at an appropriate address in said buffer.

Next, a test 1084 is performed wherein POINTER is tested to see if it is still within the bounds of the buffer. Specifically, POINTER is compared to BUFFER and to BUFF-SIZE + BUFFER which mark the two ends of the buffer. If POINTER is within the buffer, the address pointed to by POINTER is loaded with the latest value of CURRENT in step 1086. If POINTER points to either end address of the buffer, a step 1088 is performed to set a variable TOP equal to the latest value of CURRENT as symbolized by line 1090.

Next, a step 1092 is performed to determine if POINTER is less than or equal to BUFFER, the lowest address in the buffer. If it is, POINTER is set equal to BUFFER + BUFF-SIZE in step 1094. This resets POINTER to the highest address in the buffer. If POINTER is greater than BUFFER, step 1096 is performed to set POINTER to POINTER - 2. Then a step 1098 is performed to set a variable BOTTOM equal to the contents of the buffer at the address pointed to by POINTER. Finally, in step 1100, a variable SLOPE is calculated as TOP - BOTTOM. SLOPE is thus equal to the latest value of CURRENT minus the value of CURRENT stored either at the highest pair of addresses in the buffer or the previous pair of addresses. SLOPE is proportional to the slope of the load current versus drive frequency function at the current drive frequency and load current coordinates. Then processing flows via step 1102 back to step 1104 of the "peak" subroutine which vectors processing back to step 1050 of "peak" along path 1106 to increment the drive frequency again.

Returning to step 1074 of "peak", the "detector" routine is called to evaluate SLOPE at the latest I-PEAK against a constant which will separate false peaks from the real resonant peak. Figure 19 is flow chart of the "detector" routine. The first step is a test to determine if SLOPE is less than a constant MIN-SLOPE. MIN-SLOPE is picked to separate the peak at 1110 in Figure 6 from the actual resonance peak at 876. The value of MIN-SLOPE is positive and greater than the slope of any spurious antiresonance peaks or other transients. Thus, unless SLOPE is greater than MIN-SLOPE, step 1112 is never reached. Step 1112 is the step where RESONANCE is set equal to SWEEP-FREQ thereby acknowledging that the frequency at which the latest value of I-PEAK was found is probably the actual mechanical resonance frequency of the probe under the current loading condition. Note that in the preferred embodiment, this tuning process is performed upon request by the user after the user attaches the probe, places it in water and presses a button (now shown) on the front panel requesting a tuning process.

After updating RESONANCE, the flag FAILURE is reset in step 1114 to indicate that tuning was successful.

If SLOPE was less than MIN-SLOPE, step 1116 is performed to start the process of rejecting the current peak as the legitimate resonance peak by setting I-PEAK to zero. Next, step 1118 sets RESONANCE to zero, and step 1120 sets the RAILED flag to zero. Finally, step 1122 returns processing to step 994 of "analysis" where processing proceeds as previously described.

Although the invention has been described in terms of the preferred and alternative embodiments disclosed herein, those skilled in the art will appre-

driving signal;
second means coupled to said first means to occasionally determine the mechanical resonant frequency of said probe under then existing conditions and to generate said first control signal to tune said first means for generating a driving signal at said mechanical resonant frequency of said probe;
a tuning inductor means for coupling said driving signal to said probe and having an input for receiving a second control signal which controls the amount of inductance of said tuning inductor and for changing inductance in accordance with said driving signal;
means coupled to said tuning inductor and to said first means and to said second means for determining the actual phase angle between the driving signal for said probe and the resulting driving signal current and for determining the difference between said actual phase angle and a desired range of phase angles and for generating said second control signal to tune said tuning inductor to minimize said phase angle after said second means has tuned said first means to generate said driving signal at said mechanical resonance frequency of said probe.

12. The apparatus of claim 11 wherein said second means includes means for determining said mechanical resonant frequency by sweeping the frequency of said driving signal through a predetermined range of frequencies and measuring the load current drawn by said probe and for selecting as said resonant frequency, that frequency where said load current is at a peak and the slope of a function relating load current versus frequency is greater than a predetermined value.

13. A method of driving an ultrasonically driven probe comprising the steps of:

(1) sending a driving signal having a frequency within a band of frequencies to be sent to said probe;

(2) sampling and storing the amount of drive current drawn by said probe;

(3) comparing said drive current sample to the highest drive current sample previously recorded for other drive signal frequencies in said band of frequencies;

(4) calculating the slope of a function relating each drive current sample to the corresponding drive signal frequency for substantially all said drive current samples;

(5) incrementing the frequency of said driving signal;

(6) repeating steps 1 through 5 until a resonance frequency is found where the corresponding drive current sample is larger than all other drive current samples and wherein the slope of said function at said resonance frequency is greater than a predetermined constant selected to eliminate spurious current peaks caused by phenomena other than resonance from being mistaken as actual resonance peaks.

14. The method of claim 13 wherein said step of incrementing said frequency of said driving signal includes the steps of setting a coarse tuning signal at a predetermined value and incrementing a fine tuning signal to sweep through a rang of frequencies defining a window, and if said resonance frequency is not found, for changing said coarse tuning signal to a new value and incrementing said fine tuning signal to sweep through a range of frequencies defining a new window, and repeating the above described steps until said resonance frequency is found, or a determination is made that said resonance frequency cannot be found.

15. The method of claim 14 wherein steps 5 and 6 include the steps of continuing to alter said coarse tuning and fine tuning signals until said resonance frequency is located within the center 50% of frequencies of any one of said windows or frequencies swept by the incrementation of said fine tuning signal.

16. the method of claim 15 wherein said step of altering said coarse tuning signal is carried out such that each said window of frequencies somewhat overlaps each other said window of frequencies.

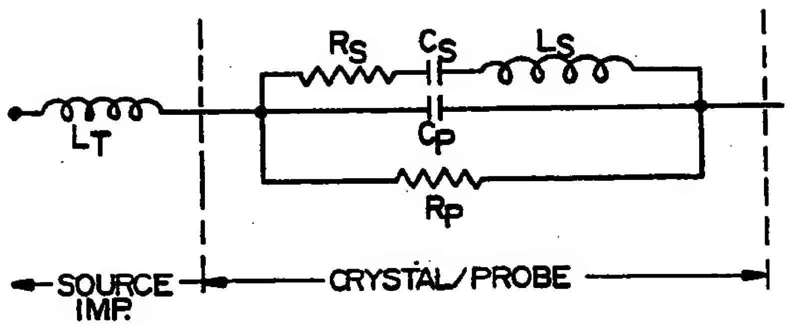

FIG. 2

$$(A)\ \omega_S = \frac{1}{\sqrt{L_S C_S}} \qquad (B)\ L_T = \frac{(R_S \| R_P)^2 C_P}{1 + \omega_S^2 C_P^2 (R_S \| R_P)^2} \text{ AT } \omega_S$$

FIG. 3

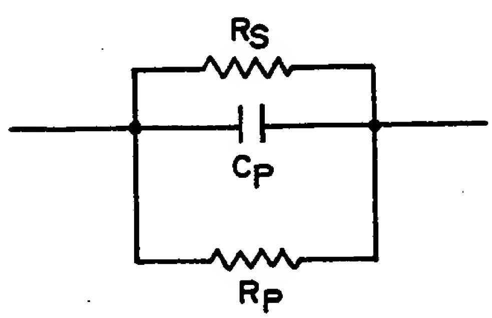

FIG. 4

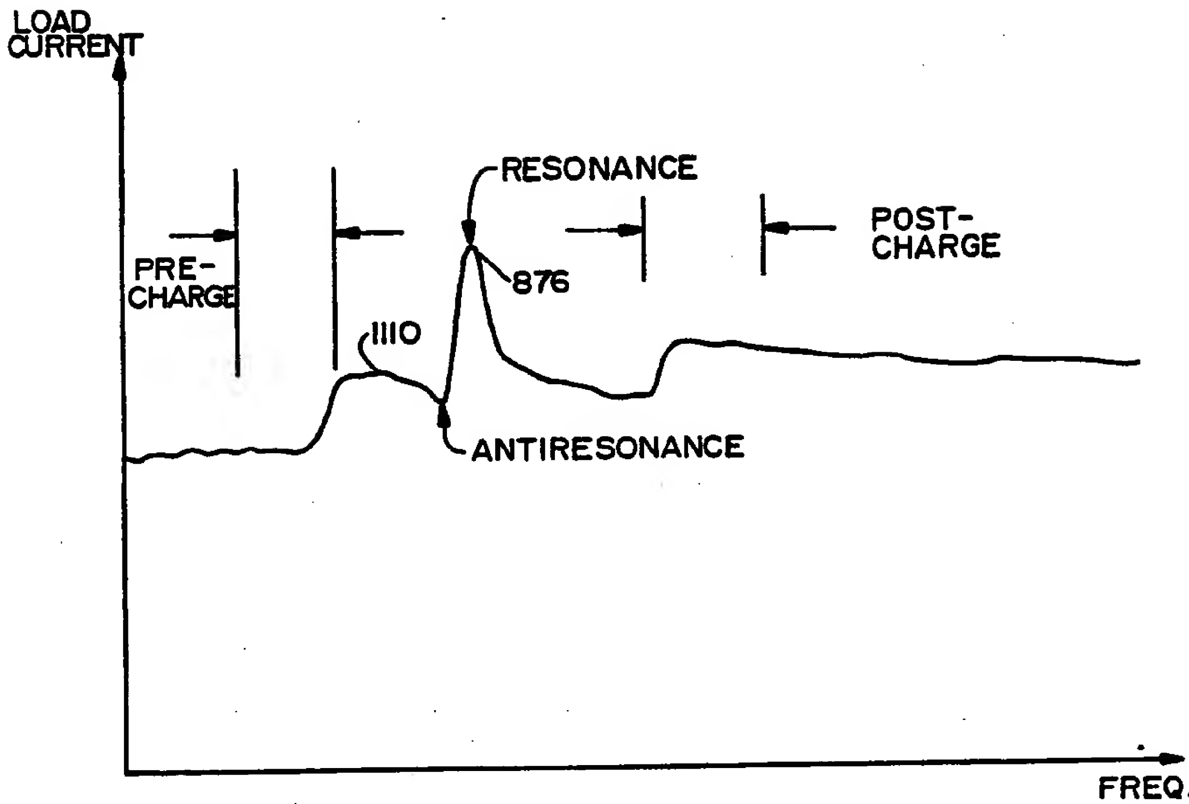
LOAD CURRENT
RESONANCE
POST-CHARGE
PRE-CHARGE
876
1110
ANTIRESONANCE
FREQ.

FIG. 6

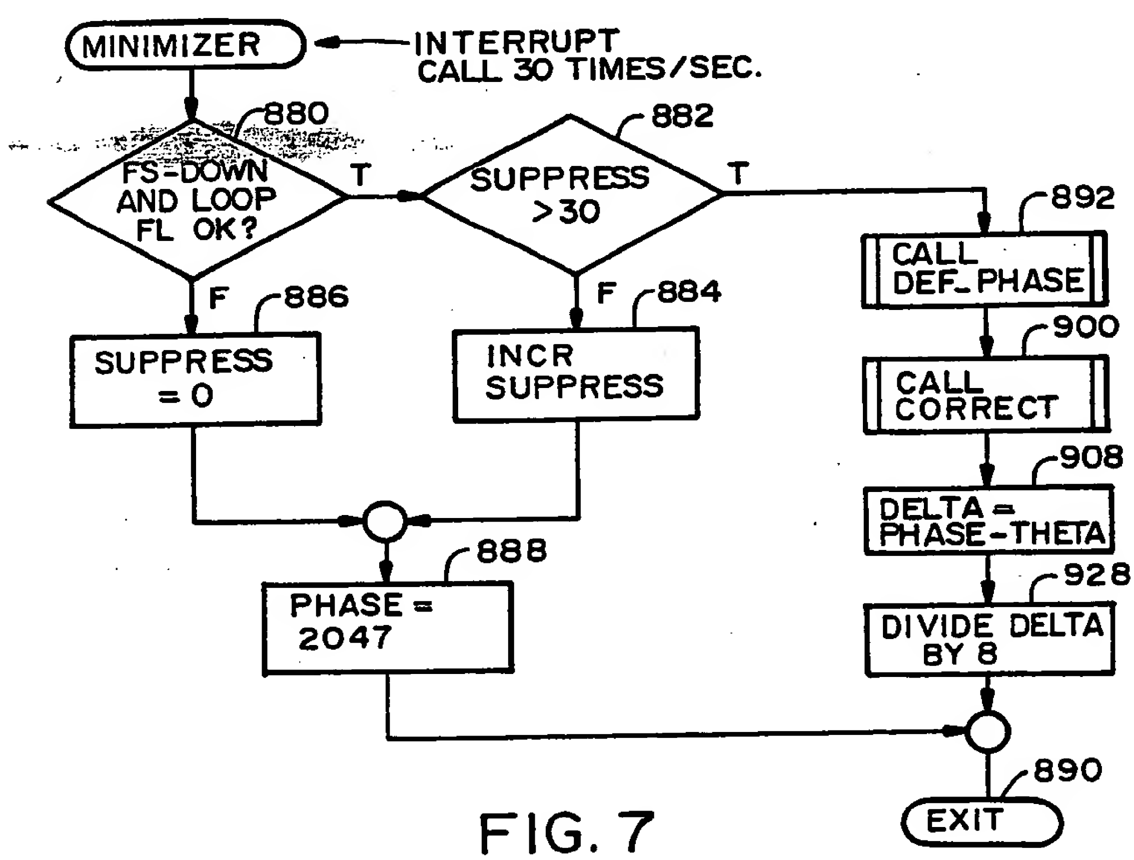
MINIMIZER
INTERRUPT CALL 30 TIMES/SEC.
880
FS-DOWN AND LOOP FL OK?
T
882
SUPPRESS >30
T
892
CALL DEF_PHASE
F
886
F
884
SUPPRESS =0
INCR SUPPRESS
900
CALL CORRECT
908
DELTA = PHASE-THETA
888
PHASE = 2047
928
DIVIDE DELTA BY 8
890
EXIT

FIG. 7

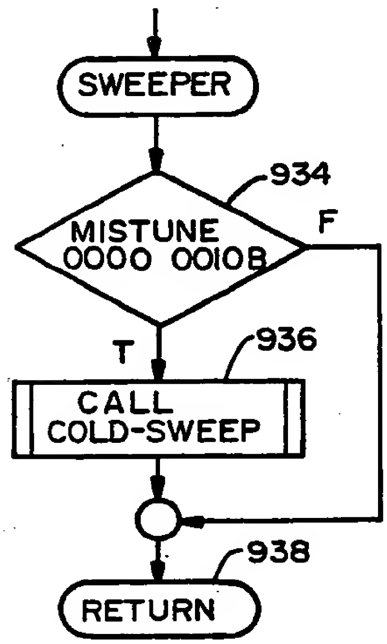

FIG. 11

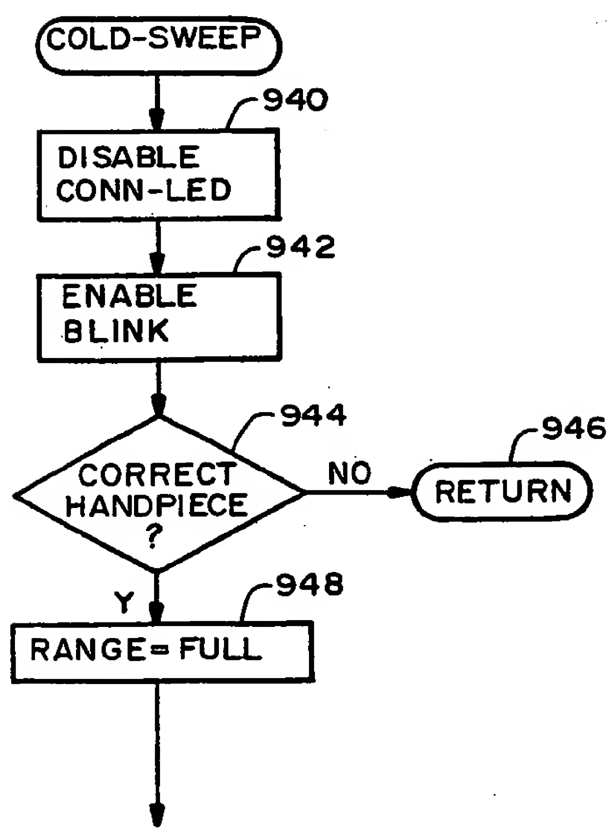

FIG. 12A

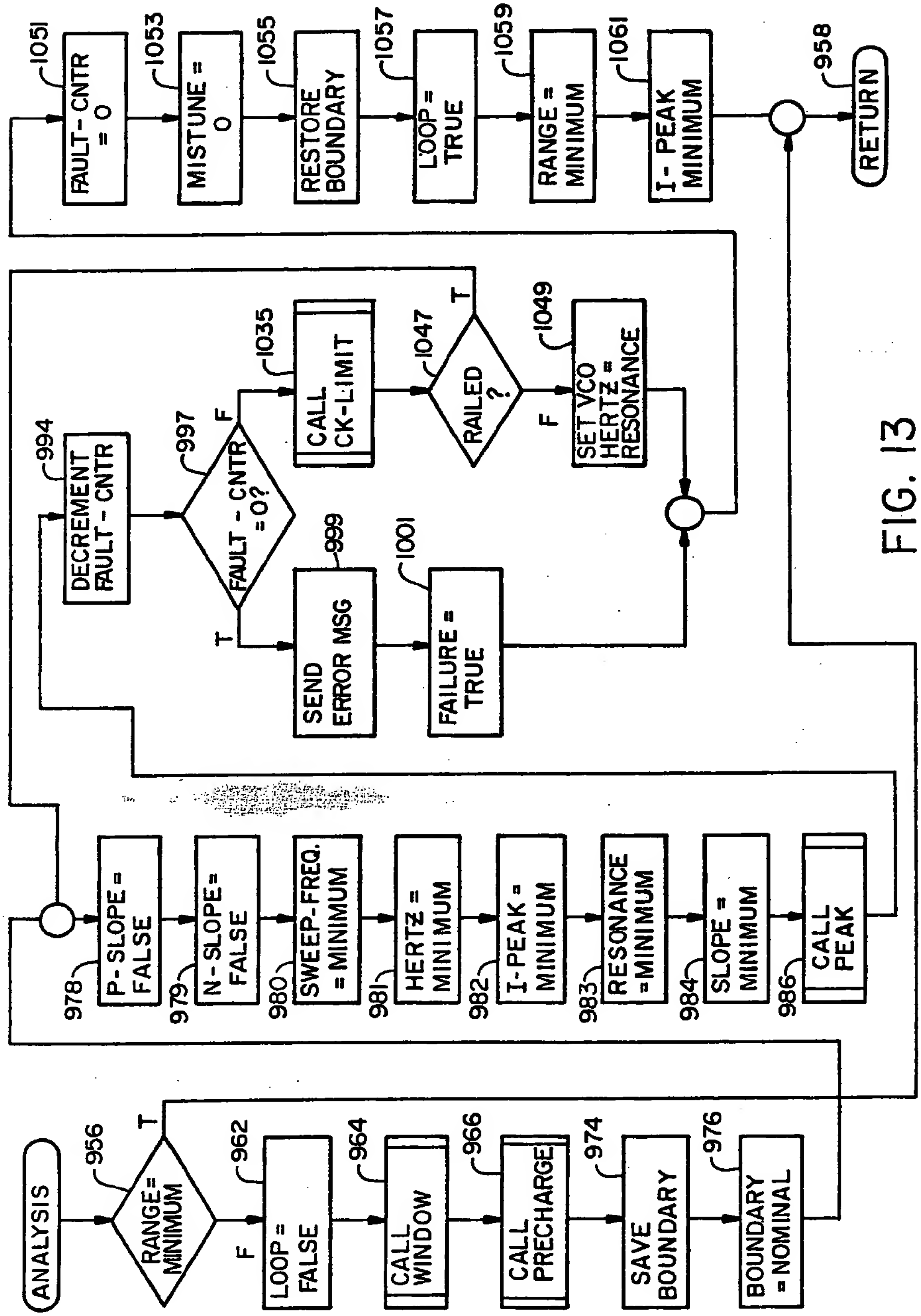
ANALYSIS
956
RANGE = MINIMUM
T
F
962
LOOP = FALSE
964
CALL WINDOW
966
CALL PRECHARGE
974
SAVE BOUNDARY
976
BOUNDARY = NOMINAL
978
P-SLOPE = FALSE
979
N-SLOPE = FALSE
980
SWEEP-FREQ. = MINIMUM
981
HERTZ = MINIMUM
982
I-PEAK = MINIMUM
983
RESONANCE = MINIMUM
984
SLOPE = MINIMUM
986
CALL PEAK
994
DECREMENT FAULT-CNTR
997
FAULT-CNTR = 0?
T
F
999
SEND ERROR MSG
1001
FAILURE = TRUE
1035
CALL CK-LIMIT
1047
RAILED ?
T
F
1049
SET VCO HERTZ = RESONANCE
1051
FAULT-CNTR = 0
1053
MISTUNE = 0
1055
RESTORE BOUNDARY
1057
LOOP = TRUE
1059
RANGE = MINIMUM
1061
I-PEAK MINIMUM
958
RETURN

FIG. 13

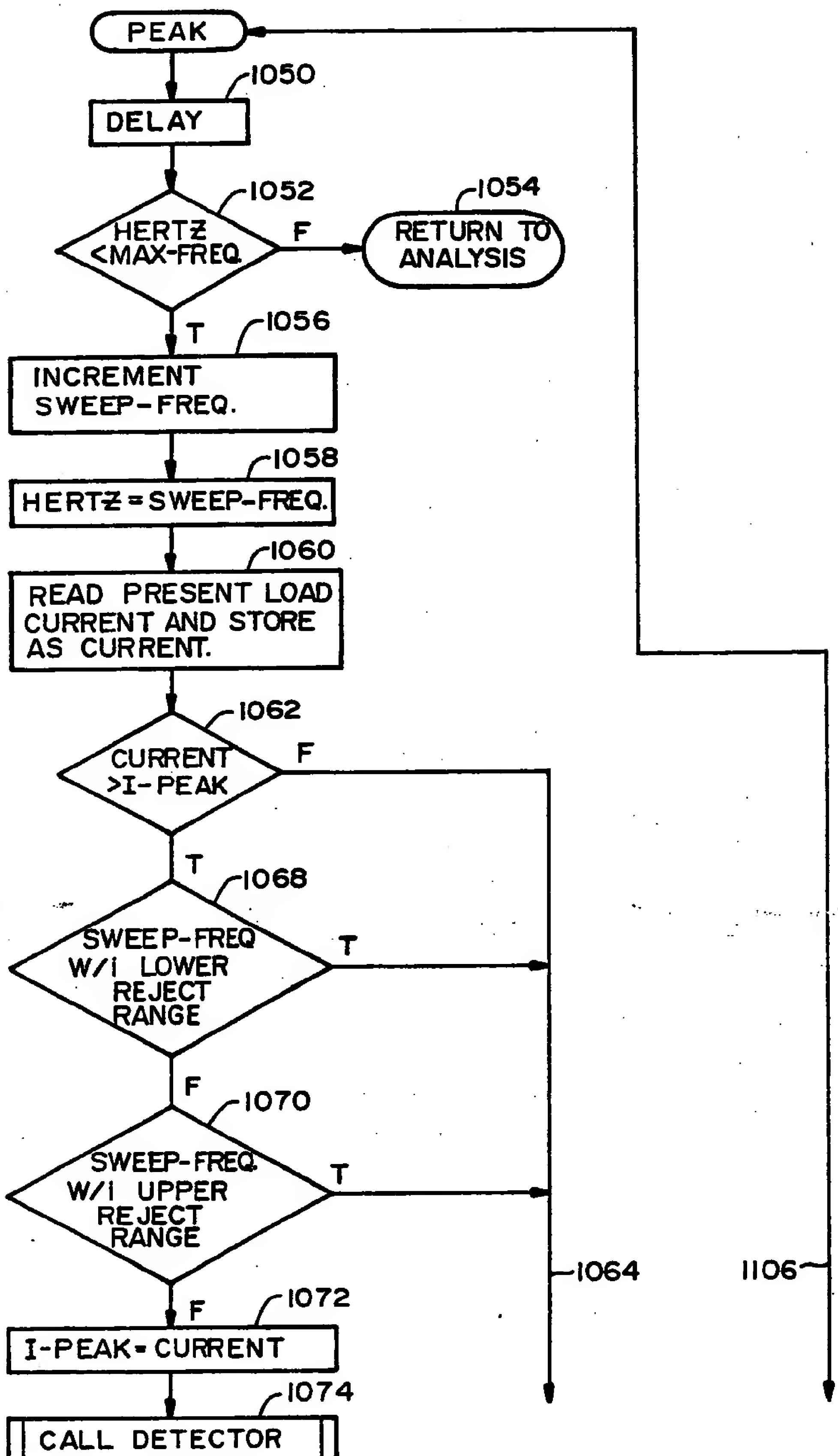
PEAK
1050
DELAY
1052
HERTZ <MAX-FREQ
F
1054
RETURN TO ANALYSIS
T
1056
INCREMENT SWEEP-FREQ.
1058
HERTZ = SWEEP-FREQ.
1060
READ PRESENT LOAD CURRENT AND STORE AS CURRENT.
1062
CURRENT >I-PEAK
F
T
1068
SWEEP-FREQ W/I LOWER REJECT RANGE
T
F
1070
SWEEP-FREQ W/I UPPER REJECT RANGE
T
F
1072
I-PEAK = CURRENT
1074
CALL DETECTOR
1064
1106

FIG. 17A

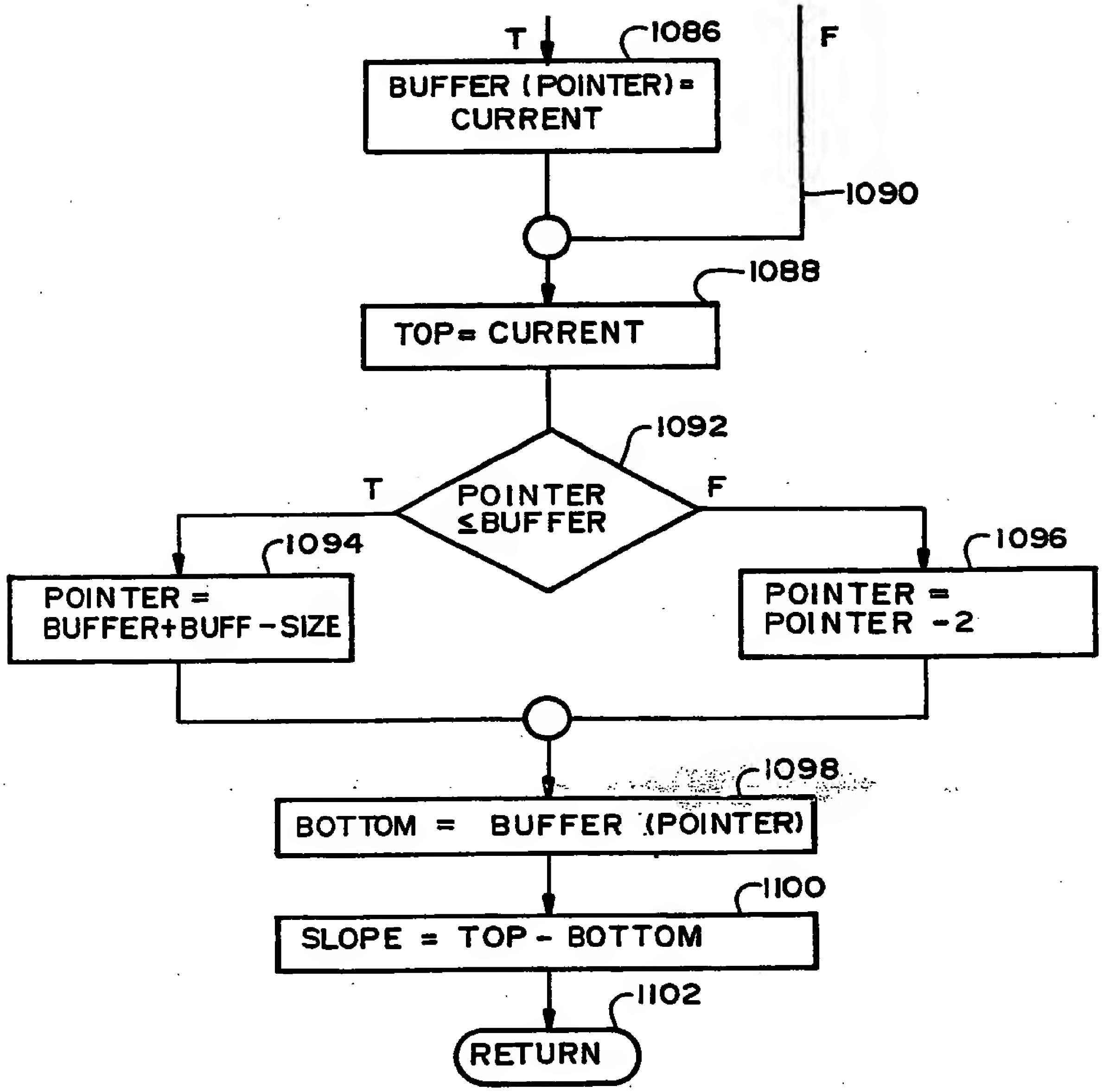
T
1086
F
BUFFER (POINTER) = CURRENT
1090
1088
TOP = CURRENT
1092
T
POINTER ≤ BUFFER
F
1094
1096
POINTER = BUFFER + BUFF - SIZE
POINTER = POINTER - 2
1098
BOTTOM = BUFFER (POINTER)
1100
SLOPE = TOP - BOTTOM
1102
RETURN

FIG. 18B

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(54) Linear power control for ultrasonic probe with tuned reactance.

(57) There is disclosed herein a driver system for an ultrasonic probe for allowing a user to have proportional control of the power dissipated in the probe in accordance with the position of power dissipation controls operable by the user and for automatically tuning upon user request such that the driving frequency is equal to the mechanical resonant frequency of said probe and such that the reactive component of the load impedance represented by said probe is tuned out. The system uses a tunable inductor in series with the piezoelectric crystal excitation transducer in the probe which has a flux modulation coil. The bias current through this flux modulation coil is controlled by the system. It is controlled such that the inductance of the tunable inductor cancels out the capacitive reactance of the load impedance presented by the probe when the probe is being driven by a driving signal which matches the mechanical resonance frequency of the probe. The resulting overall load impedance is substantially purely resistive. The system measures the phase angle and monitors the load current. This information is used to determine the mechanical resonance frequency by sweeping through a band of driving frequencies and finding the peak load current where the slope of the load current versus frequency function is greater than a predetermined constant. After the automatic tuning to the resonant frequency, the system automatically adjusts the bias current flowing through the flux modulation coil to maintain the substantially purely resistive load impedance for changing power levels. There is also disclosed herein an analog circuit to measure the Phase angle for the load driving signal and to adjust the frequency of the driving signal for best performance. This system includes an integrator to eliminate the effect of offset errors caused by operational amplifiers.

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